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RESEARCH ARTICLE

Red swamp crayfish, *Procambarus clarkii*, found in South Africa 22 years after attempted eradication

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Abstract

1. No freshwater crayfish are indigenous to continental Africa, but four species have been introduced to the continent. One of these is the North American red swamp crayfish *Procambarus clarkii*, which has been introduced into several African countries, mainly for aquaculture, and has had demonstrable impacts where it has escaped captivity. In South Africa, the documentation of this species in farm dams near Dullstroom and the adjacent Crocodile River in 1988 resulted in an eradication attempt in 1994, with unknown results.
2. In order to evaluate the status of *P. clarkii* in South Africa, dams on the previously invaded farm and the Crocodile River were sampled four times between December 2015 and June 2016 using visual surveys, trapping, dipnetting and electrofishing. This yielded a single reproductively active male *P. clarkii* from one of the farm ponds, while many other native aquatic species were found in high numbers.
3. It is clear from this study that *P. clarkii* was not eradicated in South Africa and that individuals have been surviving in the wild (i.e. outside captivity or cultivation) for at least 28 years in the location where it was introduced. Containment and eradication of the species are proposed as management actions, which have major importance in preventing undesirable further spread or translocation of this species into new aquatic environments in South Africa.

KEYWORDS
alien species, disturbance, introduction, invertebrates, pond, river

1 | INTRODUCTION

The introduction and spread of invasive species poses a threat to natural ecosystems and is widely accepted as one of the major challenges facing global biodiversity (Butchart et al., 2010). By creating novel ecological contexts, introduced species alter the structure and functioning of invaded ecosystems, often resulting in displacement, decline or even extinction of native species (Bellard, Cassey, & Blackburn, 2016; Ehrenfeld, 2010). Some of the most ecologically destructive invasions are caused by the introduction of freshwater crayfish species, high-impact invaders that can act as ecosystem engineers (Lodge et al., 2012; Matsuzaki, Usio, Takamura, & Washitani, 2009).

Although there are no indigenous freshwater crayfish species in continental Africa, four species have been introduced to the continent since the 1960s, primarily to develop an aquaculture industry (Hobbs, Jass, & Huner, 1989; Mikkola, 1996). Three of these introduced species are native to Australasia – redclaw crayfish *Cherax quadricarinatus*, smooth marron *Cherax cainii*, yabby *Cherax destructor* – and one native to North America, the red swamp crayfish *Procambarus clarkii* (Boyko, 2016). One of these species, *P. clarkii*, has a history of impacts in invaded ecosystems in Africa (Foster & Harper, 2006a; Jackson, Gery, Miller, Britton, & Donohue, 2016; Lowery & Mendes, 1977) and the others, although little is known, are likely to exert similarly strong impacts in the continent (de Moor, 2002; Nunes, Douthwaite, Tyser, Measey, & Weyl, 2016).

Of the four species, *P. clarkii* is the most established in the global aquaculture industry and, as a result, has been introduced to all continents except Australia and Antarctica (Gherardi, 2006; Hobbs et al., 1989; Holdich, Reynolds, Souty-Grosset, & Sibley, 2009). Several adaptive biological and ecological traits such as rapid growth, high fecundity, early maturity, generalist and opportunistic feeding habits, a plastic reproductive life-cycle and resistance to extreme environmental conditions make this crayfish a very successful invader (see review by Gherardi, 2006). The species has been shown to exert wide environmental impacts in invaded communities, often severely affecting the structure and functioning of natural aquatic ecosystems (reviewed in Souty-Grosset et al., 2016). As a result, *P. clarkii* has been included in the list of 'invasive alien species of Union concern' in the recent European Union Regulation on the prevention and management of the introduction and spread of invasive alien species (EU, 2014).

In Africa, *P. clarkii* has been introduced to Uganda, Rwanda, Kenya, Egypt, Sudan, Zambia and South Africa (Cumberlidge, 2009; Hobbs et al., 1989; Mikkola, 1996). Its introduction into Lake Naivasha, Kenya, in 1970 is notorious, as it became the dominant invertebrate of the lake and attained extremely high densities very rapidly (Harper et al., 2002; Lowery & Mendes, 1977; Mikkola, 1978; Smart et al., 2002). Its populations led to the almost complete elimination of floating and submerged aquatic macrophytes, as well as to a decrease in native populations of snails and freshwater crabs from adjacent rivers (Foster & Harper, 2006a, 2006b; Harper et al., 2002; Smart et al., 2002). In Naivasha, *P. clarkii* also affected fishermen's livelihoods by partially eating fish caught in gill nets and by disturbing the reproductive activity of many bottom spawning species (Loker et al., 1992; Lowery & Mendes, 1977). Furthermore, a recent study performed in a tributary of Lake Naivasha has shown that populations of the freshwater crab *Potamonautes loveni* drastically declined at sites invaded by *P. clarkii*, becoming locally extinct at one (Jackson et al., 2016). Crayfish populations also caused a marked decrease in benthic invertebrate densities and an increase in decomposition rates, once more showing that invasive crayfish can strongly affect ecosystem structure and functioning in African fresh waters (Jackson et al., 2016).

In South Africa, van Eeden, De Kock, and Pretorius (1983) reported on unconfirmed records of *P. clarkii* as early as 1962. During the 1980s, South African aquarists were rearing *P. clarkii* illegally and specimens were available in pet shops in major South African cities (van Eeden et al., 1983). Although possibly introduced as early as 1980, by 1988 a population of *P. clarkii* was confirmed present at Driehoek Farm, in the headwaters of the Crocodile River (Inkomati River Basin), close to the town of Dullstroom, Mpumalanga province (Schoonbee, 1993; Schulz, 1993). Surveys in 1991 demonstrated that the species had colonized two dams in this farm (Valleijspruit and Berry Dams) and had spread to a downstream section of the Crocodile River (Schoonbee, 1993). A subsequent survey only sampled this species from Berry Dam and resulted in a recommendation for eradication in December 1993 (Schulz, 1993). The recommended eradication method consisted of reducing the water level in the dam and physically removing crayfish by hand or using dipnets (Schulz, 1993). Following this, an eradication programme was put into practice by the Transvaal Nature and Environmental Conservation Directorate division (A. Hoffman, pers. obs.), but no report is available describing which actions were taken, the effort applied, number of harvests or subsequent monitoring. Therefore, the aim of this study was to investigate the current status of *P. clarkii* populations in South Africa, with the purpose of understanding whether or not they have been completely eradicated and of adding to the knowledge of *P. clarkii* invasions in the African continent.

2 | METHODS

2.1 | Study site

Driehoek Farm is located approximately 10 km away from the town of Dullstroom (25°28′24.50″S, 30°07′23.61″E, Figure 1) at an altitude of 1880 m above sea level, in the catchment of the Crocodile River in the Inkomati River Basin. The Crocodile River, which rises just north of Dullstroom, flows through the farm, and nine off-channel dams have been constructed to retain water and provide habitat for 'put and take' rainbow trout (*Oncorhynchus mykiss*) fishing (Mitchell, 2009). There are eight main dams at Driehoek Farm: Loch Fillan is the largest (12 ha), followed by Schoeman (2.6 ha), Berry (1.96 ha), Carp (1.12 ha), Valleijspruit (0.89 ha), Balog (0.83 ha), Baconer (0.39 ha), the smallest being Baconer1 Dam (0.17 ha) (Figure 2). All dams are predominantly fed from natural wetlands and springs, and water usually only flows through them for 3 months (or fewer) per year, in the austral summer (December to March) (B. Boshoff, pers. comm.).

Driehoek Farm has an average rainfall of about 950 mm per year, an average air temperature of 13.1°C, with the lowest air temperature of −17°C recorded when episodes of heavy snowfall occurred (MCDF, 2015; Mitchell, 2009). Average monthly water temperatures over the last 5 years ranged from 12°C in winter (June and July) to 23.5°C in summer (January), with the lowest temperature of 8°C recorded in July 2014 (Figure S1, Supporting information; MCDF, 2015).

2.2 | Sampling

From December 2015 to May 2016, all the dams at Driehoek Farm were sampled, as well as the section of the Crocodile River inside the farm, using visual surveys, traps, dipnets and electrofishing (Table 1). Carp Dam was not sampled because the water level was too low. Visual observation surveys were carried out during the day, and also at night when crayfish are usually more active (Penn, 1943). Visual observations consisted of walking along the whole margin of each water body for 5–10 min (around 0.3–0.8 km) and looking for crayfish specimens, moults or signs of burrows. Five to 10 dipnet sweeps (dimensions: 30 × 30 cm, 1 mm mesh size) were also performed along the margins of each dam and in the river. Each dam, as well as the Crocodile River, was electrofished using a handheld SAMUS 725MP, with a 10 mm mesh scoop net. Electrofishing was conducted along the margins of the water bodies during daylight, by wading for approximately 40 min per site. Seven to 10 ©Promar collapsible crayfish/crab traps (dimensions: 61 × 46 × 20 cm), baited with *c*. 100 g dry dog food, were set overnight in each dam and in the river and checked the following morning. Given that crayfish trapping efficiency has been shown to vary depending on the type of trap used (Paillisson, Soudieux, & Damien, 2011), on the third sampling session (April 2016) half of the collapsible traps were replaced with home-made funnel traps, made with a cylindrical PVC pipe having inward-facing wire funnel openings at either end (71 cm length; 16 cm diameter). In the last sampling session, 10 1.5 L plastic funnel traps, baited with fish-flavoured wet cat food, were also set at Berry Dam. Total effort for all the sampling sessions combined was 114 traps in a total of five nights, for all sampling locations. All animals captured were counted

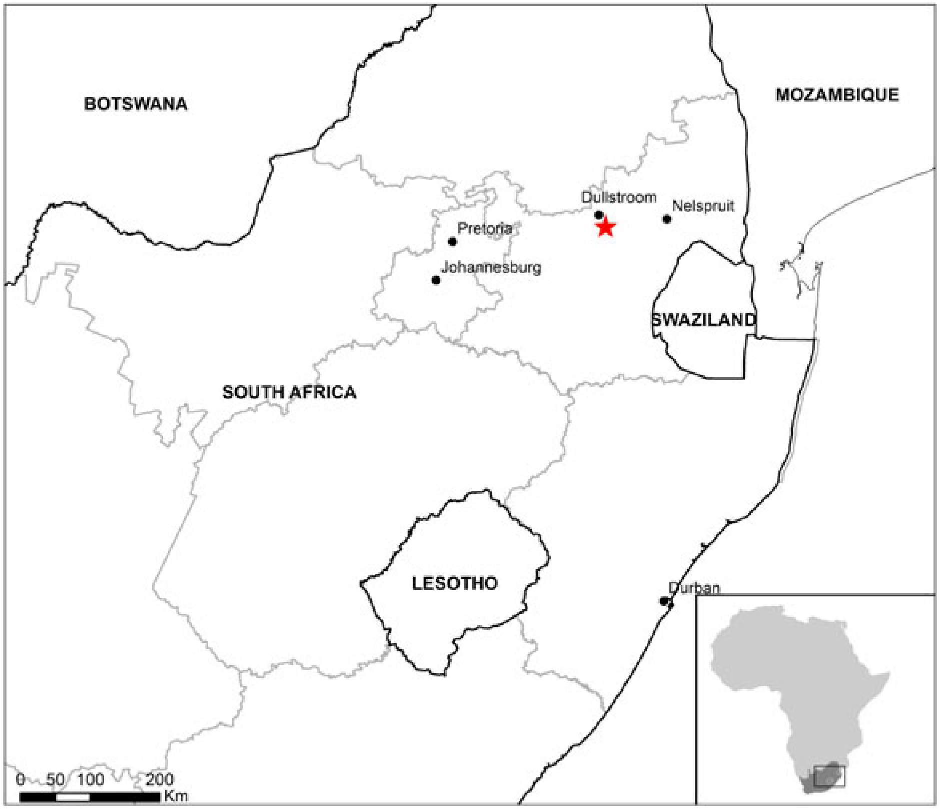

FIGURE 1 Location of Dullstroom and Driehoek Farm (red star) in South Africa

and identified to species level. Crayfish and crab specimens were photographed, sexed, measured to the nearest millimetre (cephalothorax/carapace length) and weighed to the nearest gramme. The reason for using different sampling techniques and sampling different sites in different sampling sessions (Table 1), was because this study was intended to confirm that populations of *P. clarkii* had been completely eradicated from Driehoek Farm. However, as soon as one specimen of *P. clarkii* was found, sampling effort was increased and new sampling techniques (and areas) were incorporated.

In May 2016, water quality parameters were measured at the water surface at each sampling site using a Eutech Instruments digital multi-parameter PCSTestr 35 to measure temperature (°C), pH, conductivity (μS cm^{-1}) and total dissolved solids (mg L^{-1}). Dissolved oxygen (mg L^{-1}) was measured using a Lutron DO-5510 digital oxygen meter.

FIGURE 2 Satellite view of the dams and the Crocodile River at Driehoek Farm, with an indication of where *P. clarkii* was found in 2016 (red star)

TABLE 1 Date, duration and sampling method used in each sampling session at Driehoek Farm

		Sampling session			
	Date Duration	1st sampling session December 2015 1 day	2nd sampling session March 2016 1 day	3rd sampling session April 2016 1 day	4th sampling session May 2016 2 days
Sampling method	Diurnal visual observations	X	X	X	X
	Nocturnal visual observations			X	X
	Dipnetting	X			X
	Electrofishing		X	X	X
	Trapping		X (20 traps)	X (20 traps)	X (74 traps)
	Locations in the farm sampled	Valleijspruit and Berry Dam	Valleijspruit and Berry Dam	Valleijspruit and Berry Dam; Crocodile River	All seven dams; Crocodile River

3 | RESULTS

Water temperatures at the Driehoek Farm during 2015 ranged from 16°C to 25°C, with a yearly mean of 19.8°C. For 2015 and 2016, mean temperatures were higher than those registered during the two previous years (Figure S1). Temperatures registered at each sampling site in May 2016 ranged from 15.4°C in the Crocodile River to 21.5°C in Schoeman Dam (Table 2). Berry Dam showed the next highest water temperature (19.2°C). The pH of the water bodies was quite similar and mostly ranged from 6 to 8, except for Schoeman Dam, which had a very alkaline pH of 10 (most likely caused by photosynthesis derived H^+ from aquatic macrophytes, mainly *Elodea canadensis*). Values of total dissolved solids (80–105 mg L^{-1}), as well as of conductivity (115–150 μS cm^{-1}), were similar across dams, but lower in the Crocodile River, which was expected owing to the increased volume of water flow. Dissolved oxygen in the water varied between 4.5 and 6 mg L^{-1} (Table 2).

Electrofishing and dipnetting yielded a variety of macroinvertebrates, mostly Notonectidae, Corixidae, Dytiscidae and Aeshnidae, as well as two fish species (banded tilapia *Tilapia sparrmanii* and chubbyhead barb *Enteromius anoplus*), tadpoles and newly metamorphosed striped stream frogs (*Strongylopus fasciatus*).

No crayfish specimens, moults or burrows were detected during diurnal and nocturnal visual observations, dipnetting and electrofishing, but in April 2016 one male *P. clarkii* specimen (cephalothorax length = 39 mm; weight = 14 g; Figure 3(a), (b)), reproductively active (Cambarid form I: inflated chelae, prominent copulatory hooks and cornified gonopodia; Chucholl, 2011), was sampled in one of the collapsible traps set at Berry Dam (25°28′19.03″S, 30°07′28.03″E; Figure 2).

In traps, catch per unit trap effort per night (CPUE) for *T. sparrmanii* ranged from as little as 0.8 to 22.1 individuals per trap per night in Schoeman and Berry Dams, respectively (Table S1). Individuals of *E. anoplus* were only captured in traps in Berry Dam. A maximum of eight African clawed frogs (*Xenopus laevis*) were caught in Valleijspruit Dam, in May 2016. Sidney's river crabs (*Potamonautes sidneyi*), both males and females, ranging in carapace width from 35 to 51 mm, carapace length from 29 to 49 mm and weighing up to 42 g, were captured in three of the dams in May 2016 (Table S1). The only species collected in the river were *T. sparrmanii* and *E. anoplus*, both in relatively low numbers. No fish were caught in the riffles downstream of the weir.

4 | DISCUSSION

Although listed in the Alien and Invasive Species list of the South African National Environmental Management Biodiversity Act of 2004 (updated in 2016) as a prohibited species (i.e. not present in the country) (RSA, 2016), this work shows that *P. clarkii* is present in the wild in South Africa and that this population has persisted for at least 28 years, albeit at low density. The individual caught falls under the normal range size of adult crayfish found in other populations (Chucholl, 2011) and was capable of reproduction. *Procambarus clarkii* longevity has been estimated to range generally between 3 and 6 years (see review in Dörr & Scalici, 2013), indicating multiple generations since the last detection of individuals at Driehoek Farm in 1994. These results also strongly emphasize the difficulty of eradicating invasive crayfish populations, even in a relatively confined area, as has often been shown by the failure of interventions attempted elsewhere (Hein, Zanden, & Magnuson, 2007; Peay, 2001; Peay, Dunn, Kunin, McKimm, & Harrod, 2015).

TABLE 2 Physico-chemical water parameters measured at the surface of the seven dams and Crocodile River at Driehoek Farm, in May 2016

Parameter	Loch Fillan	Schoeman Dam	Berry Dam*	Valleijspruit Dam*	Balog Dam	Baconer Dam	Baconer1 Dam	Crocodile River*
Temperature (°C)	17.8	21.5	19.2	16.2	17.8	17.2	16.9	15.4
pH	8.54	10.1	7.1	6.92	7.96	7.56	7.26	6.88
Conductivity (μS cm^{-1})	148.6	115.2	120.4	123.6	148.1	129.6	137.3	87.3
Total dissolved solids (mg L^{-1})	105.0	80.9	85.1	87.2	105.0	91.2	98.3	61.7
Dissolved oxygen (mg L^{-1})	5.7	5.8	4.5	4.5	6.0	5.3	6.0	5.6

*Water bodies which have, or at some point in time had, *P. clarkii*.

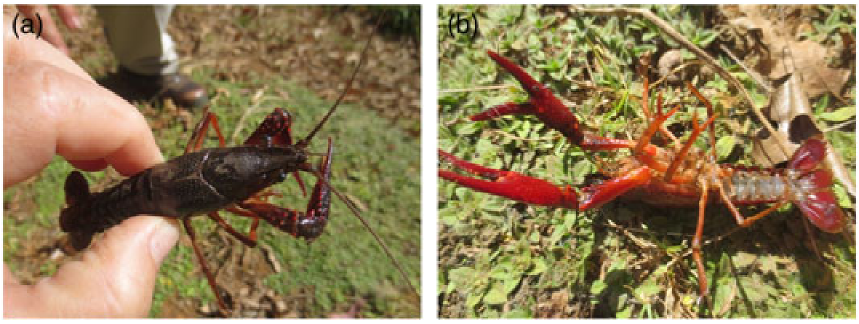

FIGURE 3 (a) Dorsal and (b) ventral view of the specimen of *P. clarkii* captured in Berry Dam, at Driehoek Farm, in April 2016

As neither Schoonbee (1993) nor Schulz (1993) give an indication of *P. clarkii* abundance before eradication (only mentioning low numbers), there are no data with which to compare current abundance to determine the impact of the 1994 eradication attempt, or if it resulted in depletion of *P. clarkii* numbers. The current CPUE of 0.1 individuals per trap per night in Berry Dam is, however, extremely low when compared with mean CPUE in traps set both in its native (CPUE =0.9–21.1 individuals per trap per night) (Bonvillain, Rutherford, Kelso, & Murphy, 2013) and introduced ranges (CPUE =0.3–22.7 individuals per trap per night) (Chucholl, 2011; Sousa, Freitas, Mota, Nogueira, & Antunes, 2013). A possible explanation might be the relatively cold temperatures experienced at Driehoek Farm during part of the year, which are known to decrease the growth, fecundity and food consumption of *P. clarkii* (Chucholl, 2011; Croll & Watts, 2004; Peruzza et al., 2015). The persistence of this population at temperatures that are unusual for this species and below its preferred range (20–25°C) (Buckle Ramirez, Herrera, Sandoval, Sevilla, & Rodriguez, 1994) reinforces the idea that *P. clarkii* has the ability to adapt to cold habitats, as has previously been shown (Chucholl, 2011; Peruzza et al., 2015; Veselý, Buřič, & Kouba, 2015). In addition, the longevity, mean lifetime, size and protein absorption efficiency of *P. clarkii* have been shown to increase at low temperature, whereas mortality usually decreases (Chen, Wu, & Malone, 1995; Chucholl, 2011; Croll & Watts, 2004), which might help explain the long-term persistence of the population in Dullstroom. Competition with freshwater crabs might also be playing a role in restricting crayfish numbers at Driehoek, as Jackson et al. (2016) found that interspecific competition between *P. clarkii* and the native river crab *Potamonautes loveni* in Lake Naivasha, Kenya, resulted in significant reduction in the diet breadth and growth rates of both species. Rainbow trout, which are constantly stocked into the farm dams might also be imposing a high predation pressure on the crayfish population, as they have been shown to be important crayfish predators elsewhere (Faragher, 1983). Although the possibility that the low numbers of crayfish sampled are due to differences in bait use (Beecher & Romaire, 2010), the inclusion of alternative baits (wet cat food) and alternative methods (dipnetting and electrofishing) yielded similar negative results.

4.1 | Proposed management actions

In South Africa the management of alien invasive organisms is a national priority and, as *P. clarkii* is listed as a prohibited species (RSA, 2016), its eradication is a legislated requirement. Although relatively isolated and apparently low in abundance, the population of *P. clarkii* at Driehoek Farm can act as a source for either new translocations or secondary dispersal in the country. According to de Moor (2002), *P. clarkii* is likely to survive natural temperature regimes throughout South Africa, owing to its tolerance to a wide range of temperatures and resistance to extremely low levels of dissolved oxygen. As *P. clarkii* has been shown to affect the trophic structure of freshwater communities elsewhere (reviewed in Souty-Grosset et al., 2016), this species could have devastating impacts on freshwater ecosystems in South Africa (de Moor, 2002).

Several mechanical (trapping, electrofishing, hand removal), physical (drainage, barriers), chemical (biocides), biological (natural predators or pathogens) and autocidal (sterile male release or sex pheromones) methods have been proposed to control or eradicate alien crayfish populations (reviewed in Freeman, Turnbull, Yeomans, & Bean, 2010; Gherardi, Aquiloni, Diéguez-Uribeondo, & Tricarico, 2011). However, crayfish eradication only seems possible for populations in small enclosed water bodies (reviewed in Gherardi et al., 2011), indicating that the low abundance and apparently confined *P. clarkii* population at Driehoek Farm presents a good opportunity for re-attempting eradication. The failure of the previous eradication attempt in 1994 reinforces the difficulty in eradicating crayfish populations and calls for different actions to be carried out now, in order to achieve success.

Although chemical treatments, mostly using rotenone or synthetic pyrethroids, seem to be the only effective technique in eradicating crayfish populations from small water bodies (Peay, Hiley, Collen, & Martin, 2006; Sandodden & Johnsen, 2010), these products are not specific for crayfish, being toxic to other crustaceans, insects, and fishes (Peay et al., 2006). Furthermore, while rotenone has been used successfully for the eradication of alien fishes in South Africa (Weyl, Finlayson, Impson, & Woodford, 2014), the concentrations required to kill crayfish (*Procambrus acutus*, 4 mg L^{-1}) (Wujtewicz, Petrosky, & Petrosky, 1997) are not only 40 times higher than those generally used in fish treatments, but also greatly surpass the maximum treatment concentration of 0.2 mg L^{-1} approved for resistant species in the USA (Finlayson et al., 2010). Taking this into account, either total dewatering or the use of mechanical techniques such as intensive trapping, using different types of traps and baits, repeated electrofishing and hand removal, by recurring scuba diving or snorkelling, should be considered as alternative options. If mechanical methods are to be used, it is important that sustained effort is applied over the course of a year. In addition, it is important that any eradication attempt includes comprehensive monitoring to evaluate whether the intervention has achieved the desired objective. For this, and while the survey methods used in the current study are applicable for monitoring, additional techniques such as the use of environmental DNA (which has recently been used to detect and estimate abundance of *P. clarkii*) (Tréguier et al., 2014) should be evaluated and included, if appropriate. It is important, too, that any eradication attempt is accompanied by an education campaign to inform members of the public on the impacts of crayfish invasions, in order to mitigate against the possibility of future introductions.

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SUPPORTING INFORMATION

Additional Supporting Information may be found online in the supporting information tab for this article.

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